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LIQUID INFLOW TO INITIALLY EMPTY, HEMISPHERICAL ENDED CYLINDERS DURING WEIGHTLESSNESS

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Cleveland, Ohio

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ABSTRACT

An experimental investigation was conducted in a weightless environment during which liquid was pumped into hemispherical ended cylinders which were initially void of liquid. During inflow, two distinct types of liquid-vapor interfaces were observed; a stable interface and an unstable interface. The stability of the liquid-vapor interface was correlated by a Weber number based on inlet line radius and inlet velocity. Results indicate that above a Weber number of 1.3, the interface became unstable. Furthermore, this filling process was independent of the radii of the experiment tanks (2 to 4 cm). No gross effects due to the viscosity of the test liquid were observed.

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SUMMARY

An experimental investigation was conducted in a weightless environment during which liquid was pumped into hemispherical ended cylinders which were initially void of liquid. During inflow, two distinct types of liquid-vapor interfaces were observed; a stable interface and an unstable interface. The stability of the liquid-vapor interface was correlated by a Weber number based on inlet line radius and inlet velocity. Results indicate that above a Weber number of 1. 3, the interface became unstable. Furthermore, this filling process was independent of the radii of the experiment tanks (2 to 4 cm). No gross effects due to the viscosity of the test liquid were observed.

INTRODUCTION

In-orbit propellant transfer (refueling) and the transfer of liquids between containers as in regenerative life support systems will be required for future long range missions. The knowledge of both the outflow characteristics from a storage tank and the subsequent fluid behavior during filling of the receiver tank under weightlessness is required for the design of these transfer systems.

An extensive program dealing with liquid transfer in a weightless environment is being conducted at the Lewis Research Center. Most of the work to date has dealt with the liquid outflow or pumping phase of weightless fluid transfer. The initial work done in this area by Nussle (ref. 1) brought to attention the need for baffling of inlets and outlets of containers. Subsequent work by Derdul (ref. 2) has yielded results for predictions of the distortion of the liquid-vapor interface during outflow. The first work studying the phenomena of fluid behavior during filling or inflow by Andracchio (ref. 3) showed that transferring liquid in weightlessness was possible and that baffling greatly improved the filling performance.

The purpose of this investigation was to determine the behavior of the liquid-vapor interface during weightlessness when liquid is pumped into hemispherical ended cylindrical tanks. The experiment tanks were initially void of liquid, unbaffled, and had inner radii varying from 2 to 4 centimeters. Inlets to the tanks were circular in cross section, located along the longitudinal tank axis and had inner radii varying from 0.2 to 0.8 centimeter. Three test liquids with zero degree static contact angles were chosen to give a range of specific surface tensions and viscosities. All data was obtained in the Lewis Research Center's Drop Tower Facility.

SYMBOLS

A_i	cross sectional area of inlet line, cm^2
F_{mf}	force due to momentum flux, dynes
F_{st}	force due to surface tension, dynes
g	acceleration due to gravity, 980 cm/sec^2
R_i	radius of inlet line, cm
R_t	radius of tank, cm
t	time during weightless drop, sec
$V_{i,avg}$	average inlet velocity, cm/sec
W_e	Weber number, $W_e = (V_{i,avg})^2 R_i/2\beta$
β	specific surface tension, σ/ρ, cm^3/sec^2
μ	absolute viscosity, gm/cm-sec
ρ	liquid density, gm/cm^3
σ	surface tension, dynes/cm

APPARATUS AND PROCEDURE

Test Facility

The experimental investigation was conducted in the Lewis Research Center's Drop Tower Facility shown in figure 1. This facility provides 2.2 seconds of weightless

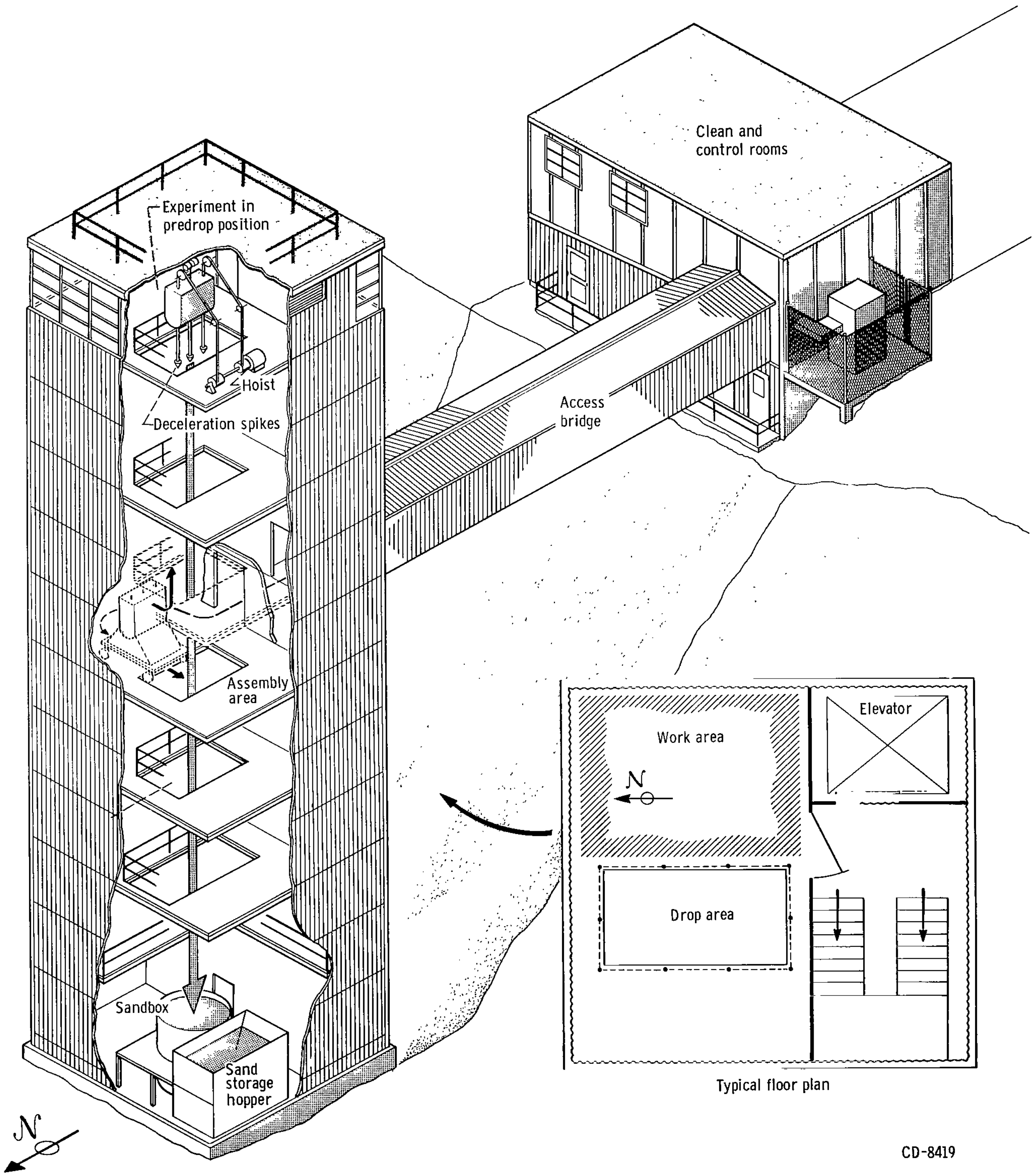
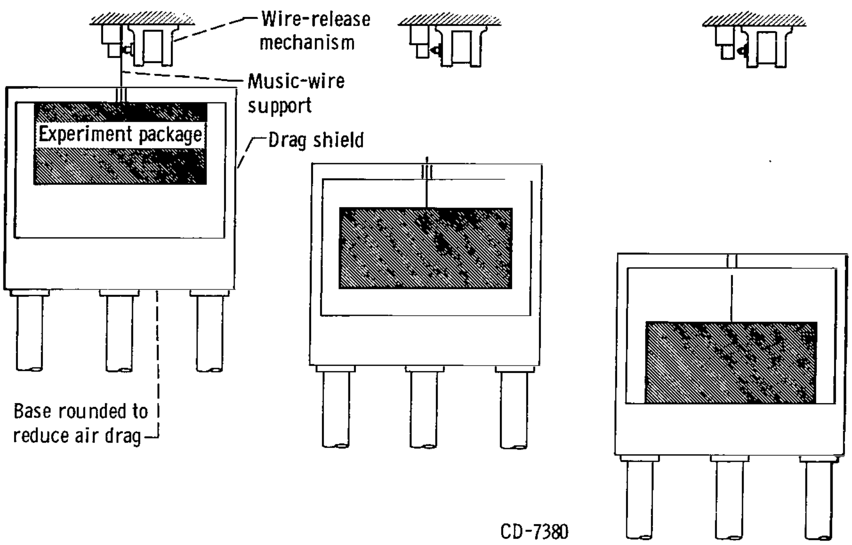


Figure 1. - Drop tower facility.



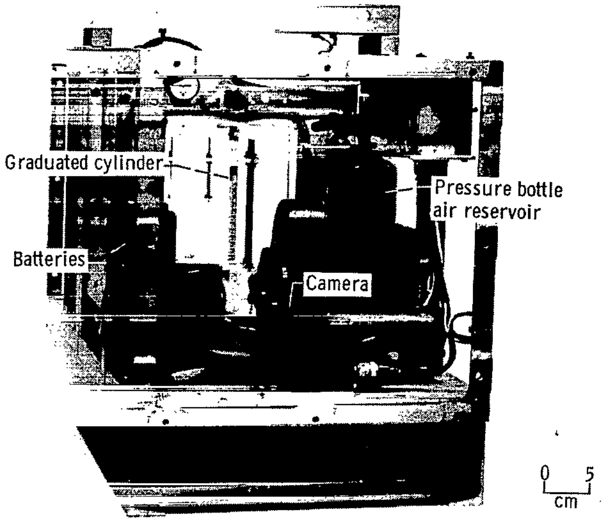
(a) Before test drop. (b) During test drop. (c) After test drop.

Figure 2. - Position of experiment package and drag shield before, during, and after test drop.

free-fall by allowing an experimental package to fall a distance of 26 meters while enclosed in a protective drag shield. Acceleration as a result of air drag on the experiment package is maintained below 10^{-5} g by the drag shield which has a high weight-to-frontal area and a low drag coefficient. The package and the drag shield fall simultaneously but are independent of each other during the drop as shown in figure 2. At the conclusion of the drop, the package is decelerated in a bed of sand at an average deceleration rate of 15 g's. A complete description of the test facility can be found in reference 4.

Experiment Package

The experiment package shown in figure 3 is a self-contained unit consisting of the experiment tank, a photographic system, a digital clock, a pumping system and an electrical system to operate the various components. The experiment tank is indirectly illuminated so that the behavior of the liquid-vapor interface may be recorded with a 16-millimeter camera. Also in the field of view of the camera is a digital clock with a calibrated accuracy of 0.01 second. An air reservoir, graduated cylinder, metering valve and solenoid valve make up the pumping system. The volume of the air reservoir was made large (apporimately 30 to 1) with respect to the liquid removed from the graduated cylinder so that no significant pressure decrease occurred during pumping. All electrical components were operated through a control box and received their power from rechargeable nickel-cadmium cells.



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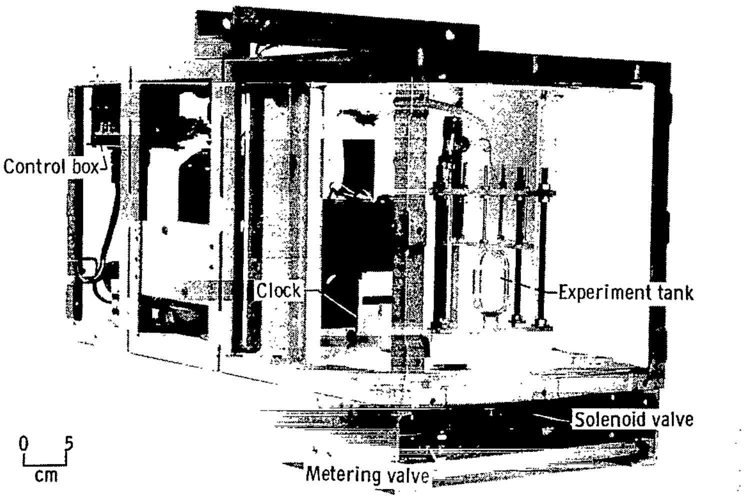

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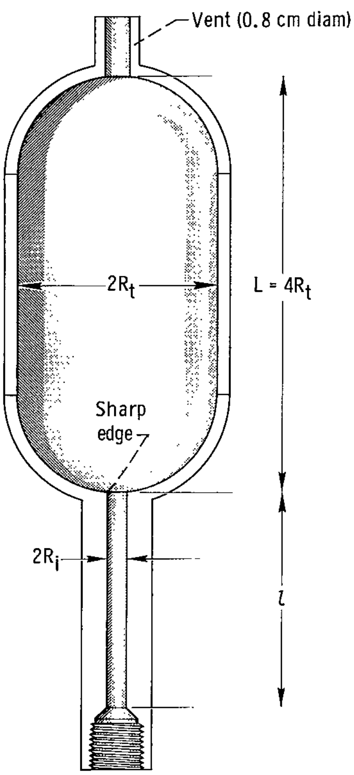
Figure 3. - Propellant transfer experiment package.

TABLE I. - PROPERTIES OF TEST LIQUIDS

[Contact angle with cast acrylic plastic in air, 0°]

Liquid	Surface tension at 20° C, σ, dynes/cm	Density at 20° C, ρ, gm/cm^3	Viscosity at 20° C, μ, gm/cm-sec	Specific surface tension, β, cm^3/sec^2
Anhydrous ethanol	22.3	0.789	1.2×10^{-2}	28.3
Trichloro-trifluoro-ethane	18.6	1.579	0.7×10^{-2}	11.8
Butanol	24.6	0.809	2.9×10^{-2}	30.4



Tank radius, R_t, cm	Inlet line radius, R_i, cm	Inlet line length, l, cm
2	0.2	4
2	.4	4
3	.3	6
3	.6	6
4	.2	8
4	.4	8
4	.8	8

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Figure 4. - Typical experiment tank.

The experiment tanks used in this investigation were hemispherical ended cylinders with a length to diameter ratio of two. As shown in figure 4, the three tank sizes tested were 2, 3, and 4 centimeters in radius. All of the tanks were machined from cast acrylic rod and polished for photographic purposes. Separate inlet sections were available for each tank size so that the ratio of tank radius to inlet radius could be varied. All inlet lines had a length of at least 10 radii and terminated with a sharp edge as shown in figure 4. Each tank was also open to the atmosphere through a vent located opposite the inlet and along the longitudinal axis of the tank.

The liquids used in this investigation were anhydrous ethanol, butanol and trichlorotrifluoroethane. Properties, pertinent to this study, are given in table I. These particular liquids were chosen to be representative of the range of specific surface tensions exhibited by the majority of the liquids presently in use in spacecraft systems. In all cases, the liquids were wetting, that is, they had an essentially zero degree static contact angle with acrylic plastic to duplicate the static contact angle on typical tank materials. To improve photographic quality, a small amount of dye was added to the liquid. This dye had no measurable effect on the fluid properties.

Operating Procedure

The operating procedure consisted of a thorough cleaning of parts of the experiment, assembly of the cleaned equipment, priming of the system, a calibration check and finally the weightless test.

The tank and all the lines which contacted the test liquid were first cleaned in an ultrasonic cleaner using a mild aqueous detergent solution to assure that liquid properties would not be effected by contaminants. The parts were then rinsed with distilled water and dried in a warm air dryer. The system was then assembled as shown in figure 5 and mounted in the package.

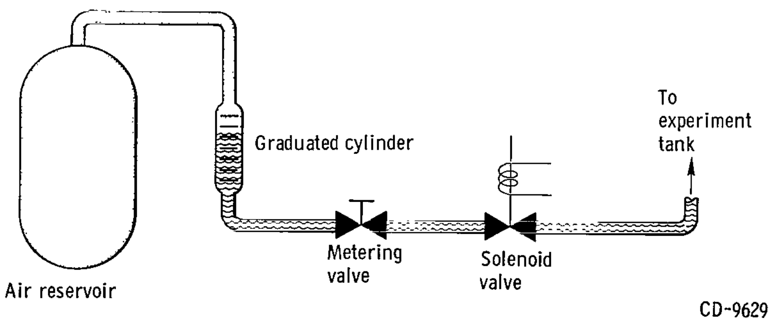


Figure 5. - Propellant flow schematic.

The system was then filled with liquid and activated several times to remove any air in the liquid lines and to check for possible leaks. After this priming, a calibration run was made to set the flow rate at the desired value by varying the setting of the in-line metering valve.

In preparation for the weightless drop, the desired amount of liquid was placed in the graduated cylinder, the tank emptied of residual liquid, and the required pressure supplied to the air reservoir. The camera was then loaded and the package balanced about the horizontal axes. After balancing, the package was placed in the drag shield and hoisted to the predrop position where the entire assembly was suspended with a music wire. A cutter, driven with compressed air, notched the wire causing it to fail. Pumping to the initially empty tank began at the instant the wire failed and the package entered weightlessness.

Data Reduction

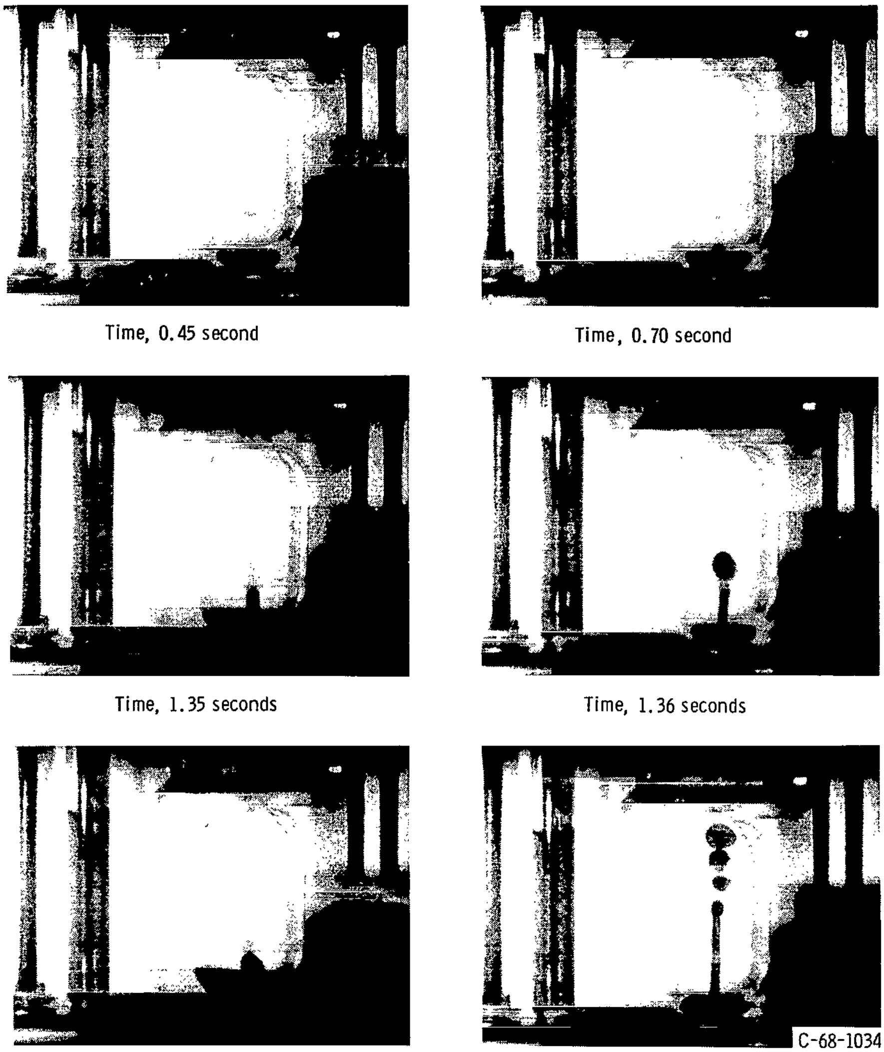
All data was recorded on 16-millimeter color film. Flow rate out of the graduated cylinder and into the tank could be directly determined by reading the position of the liquid in the graduated cylinder and the time on the digital clock. Knowing this flow rate, the average inlet velocity was calculated.

RESULTS AND DISCUSSION

Description of Inflow Geysering Phenomena

In examining some of the early test films, two distinct regions of interface behavior were noted; a stable region and an unstable region. In the first or stable region, some geysering of the incoming liquid occurred over the inlet. The geyser grew to some height with respect to the liquid-vapor interface and then either remained at that height or decreased in height with respect to the lowest point on the interface. In this region, a quantity of liquid was being collected near the inlet end of the tank.

In the unstable region, the geyser grew in height with respect to the lowest point on the liquid-vapor interface. In some cases, the geyser remained a continuous column of liquid; while in other cases, the geyser broke up into drops which continued to move toward the vent end of the tank. In both of these cases, only a small amount of the liquid entering the tank collected near the inlet, and liquid either impinged on the vent end of the tank or apparently would have if more weightless time were available.



Time, 0.45 second

Time, 0.70 second

Time, 1.35 seconds

Time, 1.36 seconds

Time, 2.13 seconds

(a) Stable; inlet velocity, 9.95 centimeters per second.

Time, 2.13 seconds

(b) Unstable; inlet velocity, 13.9 centimeters per second.

Figure 6. - Interface stability regions during inflow. Tank radius, 2 centimeters; inlet radius, 0.2 centimeter; liquid trichlorotrifluoroethane.

A photographic sequence depicting both stable and unstable interface behavior is shown in figure 6 for a 2-centimeter radius tank with a 0.2-centimeter inlet radius. In the stable region, figure 6(a), note that the liquid geyser has reached a terminal height of about 2 centimeters with respect to the lowest point on the interface at $t = 1.35$ seconds and remains at this height for the remainder of the test. However, in the unstable region, figure 6(b), the liquid geyser has broken up into drops and these drops are about to impact the vent at $t = 2.13$ seconds.

Discussion of Weber Number Criterion

As a result of the observations of stable and unstable interface behavior, consideration was given to the development of a dimensionless grouping which could be useful in scaling the experimental results. The only forces considered to be significant in delineating between the regions of stability and instability of the interface are those due to the incoming momentum flux and the surface tension. When the incoming momentum flux is small compared to the force due to surface tension, the liquid-vapor interface should be stable. When the incoming momentum flux becomes sufficiently large, it should overcome the surface tension force resulting in an unstable geysering configuration. The ratio of these forces, therefore, should delineate the regions of stability and instability for liquid inflow.

The incoming momentum flux may be expressed in terms of the average inlet velocity, $V_{i, avg}$, as follows:

$$F_{mf} = \rho A_i V_{i,avg}^2 = \rho \pi R_i^2 V_{i,avg}^2 \tag{1}$$

where ρ = liquid density and R_i = inlet radius. The surface tension force may be given as:

$$F_{st} \propto 2\pi R_i \sigma \tag{2}$$

where σ = surface tension of the liquid. Taking the ratio of these two forces yields:

$$\frac{F_{mf}}{F_{st}} \propto \rho \frac{V_{i,avg}^2 R_i}{2\sigma} \tag{3}$$

which is the Weber number based on inlet velocity and radius. Substituting the specific surface tension, β for σ/ρ in equation (3) results in

$$W_e = \frac{F_{mf}}{F_{st}} \propto \frac{V_{i,avg}^2 R_i}{2\beta} \tag{4}$$

Experimental Verification of the Weber Number Criterion

To verify the Weber number as the proper scaling parameter for liquid inflow, inlet velocity was plotted against the ratio of specific surface tension to tank inlet radius over the range of fluid properties and tank radii investigated. The results are shown in

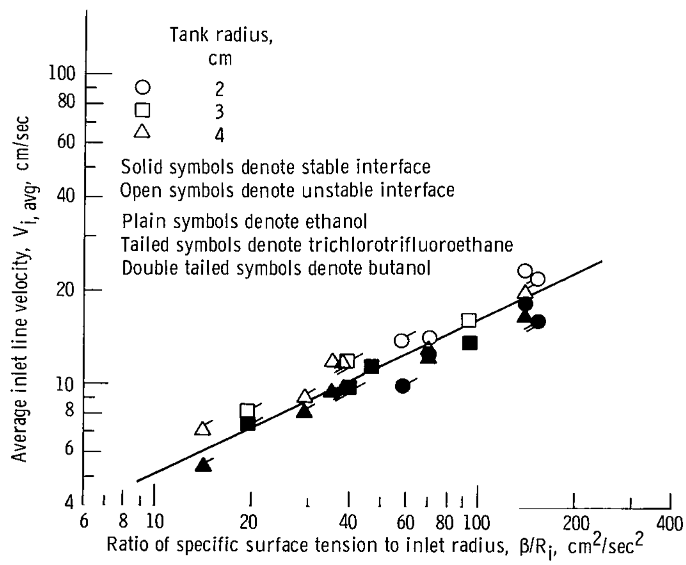


Figure 7. - Stability of liquid-vapor interface delineated by Weber number.

figure 7. The solid symbols indicate the highest inlet velocity for which the liquid-vapor interface was considered stable while the open symbols denote the lowest inlet velocity for which the liquid vapor interface was unstable. Thus, the actual velocity for the transition from stable to unstable interface behavior occurred somewhere between these two values. The line drawn in figure 7 indicates the transition between the two regimes and can be represented by a Weber number of 1.3. (For exact values of plotted points, refer to table II.)

It should be noted that, since one line delineates between the regions of stability and

TABLE II. - LIST OF DATA

Tank radius, R_t, cm	Inlet radius, R_i, cm	Test liquid	Inlet velocity, $V_{i,avg}$, cm/sec	Interface
2	0.2	Ethanol	18.25	Stable
			23.6	Unstable
		TCTFE[a]	9.95	Stable
			13.9	Unstable
		Butanol	15.9	Stable
			22.2	Unstable
	0.4	Ethanol	12.9	Stable
			14.1	Unstable
3	0.3	Ethanol	13.6	Stable
			16.0	Unstable
		TCTFE[a]	9.6	Stable
			11.7	Unstable
	0.6	Ethanol	11.5	Stable
		TCTFE[a]	7.52	Stable
			8.15	Unstable
4	0.2	Ethanol	15.7	Stable
			19.9	Unstable
	0.4	Ethanol	12.7	Stable
			12.9	Unstable
		TCTFE[a]	8.05	Stable
			8.95	Unstable
	0.8	Ethanol	9.6	Stable
			11.9	Unstable
		TCTFE[a]	5.36	Stable
			7.05	Unstable
		Butanol	9.7	Stable
			11.4	Unstable

[a]Trichlorotrifluoroethane.

instability for all tank radii, no effect of tank radius was evident. Also, no gross effects due to viscosity were observed, since nearly the same velocity caused instability for ethanol and butanol which differ in viscosity by a factor of 2.5 to 1. Therefore, the results of this experiment indicate that the Weber number based on inlet radius and inlet velocity, is a nondimensional scaling parameter useful in delineating between the regions of stable and unstable interface behavior during the filling of an initially empty, hemispherical ended tank.

APPLICATIONS

The Weber number criterion delineating the regions between stable and unstable interface behavior indicates that inflow behavior can be accurately predicted for any size tank of the configuration studied. However, this criterion indicates that it becomes impractical to perform transfers in large unbaffled tanks because the allowable inlet velocity is relatively low. For example, in a liquid hydrogen tank of radius 10 feet (304.9 cm) and inlet radius 0.5 feet (15.2 cm), the maximum inlet velocity that will still maintain an essentially stable liquid-vapor interface is 2.37 centimeters per second. At this small inlet velocity, a tank of these dimensions would require about 48 hours of filling time. However, it is conceivable that this time could be considerably decreased by the addition of inflow baffles such as those employed in reference 3. On the other hand, for a small reaction control tank of radius 6 inch (15.2 cm) and inlet radius 0.6 inch (1.52 cm) using arizine 50, the maximum inlet velocity that will maintain an essentially stable liquid-vapor interface is 7.6 centimeters per second. At this velocity, the tank would require only about 10 minutes of filling time.

From the vast differences in filling time for these two examples, it is evident that the most practical application for liquid transfer to unbaffled, hemispherical ended tanks would occur when the tank is small. It appears, therefore, that this mode of in-orbit liquid transfer would be of value in the transfer of liquids into such tanks as are presently being considered for reaction control systems, fuel cells and possibly for water collection in closed loop life support systems.

SUMMARY OF RESULTS

An experimental investigation of the stability of the liquid-vapor interface during liquid inflow to initially empty hemispherical ended cylinders was conducted in a weightless environment. The tests were conducted over a range of inlet radii (0.2 to 0.8 cm), tank radii (2 to 4 cm), and liquid properties. The following results were obtained:

1. During inflow, two types of interface behavior were observed:
   (a) At low inlet velocity, a geyser formed and grew to some height with respect to the lowest point on the liquid-vapor interface and was then stabilized by surface tension.
   (b) At high inlet velocity, a geyser formed and liquid impacted the opposite (vent) end of the tank.

2. The Weber number based on inlet radius and inlet velocity delineated a region between stable and unstable interface behavior. The value of the critical Weber number was determined to be 1.3.

3. The stability of the liquid-vapor interface was independent of the tank radius and the viscosity of the test liquids over the ranges investigated.

Lewis Research Center,
National Aeronautics and Space Administration,
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